UK-RAS White Papers

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UK-RAS
NETWORK
ROBOTICS & AUTONOMOUS SYSTEMS

Robotic and Autonomous Systems for Resilient Infrastructure

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FOREWORD

Welcome to the UK-RAS White Paper Series on Robotics and Autonomous Systems (RAS). This is one of the core activities of UK-RAS Network, funded by the Engineering and Physical Sciences Research Council (EPSRC). By bringing together academic centres of excellence, industry, government, funding bodies and charities, the Network provides academic leadership, expands collaboration with industry while integrating and coordinating activities at EPSRC funded RAS capital facilities, Centres for Doctoral Training and partner universities.

The environment that infrastructure RAS is required to operate presents many challenges. For example, robots in cities must cope with the risks created from the complex interaction between large numbers of people and vehicles. Robots in tunnels or mines must cope with rough terrain, narrow passageways, and degraded perception. Offshore and subsea infrastructure robots must withstand extreme cold and pressure operating at depth. Furthermore, robots undertaking nuclear decommissioning must withstand radiation and restricted access. In general, robots must be able to resist chemicals and materials used in the construction process as well as being resistant to dirt, dust and robust to large forces exerted. Common to all these environments, the robots need significant levels of autonomy with effective self-monitoring, self-reconfiguration and repair.

This whitepaper outlines the global trends in infrastructure robotics and presents our future vision towards ‘zero’ disruption to human activity and ‘zero’ environmental impact for infrastructure maintenance. It outlines the UK strategy and investment in this critical area and how to work together to boost our international competitiveness. The UK-RAS white papers are intended to serve as a basis for discussing the future technological roadmaps, engaging the wider community and stakeholders, as well as policy makers in assessing the potential social, economic and ethical/legal impact of RAS. It is our plan to provide annual updates for these white papers so your feedback is essential - whether it be pointing out inadvertent omissions of specific areas of development that need to covered, or major future trends that deserve further debate and in-depth analysis. Please direct all your feedback to white-paper@ukras.org.

We look forward to hearing from you!

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EXECUTIVE SUMMARY

Our economic infrastructure is the dense network of systems providing energy, transport, water, waste management, telecommunications and flood defence that enable the essential services on which our everyday activities depend. An effective infrastructure requires continuous activity; creation, inspection, repair, maintenance, renewal and upgrading to satisfy society's ever-increasing requirements for the connectivity, mobility and access to resources that underpin economic prosperity. The engineering processes associated with this activity can interrupt physical infrastructure, impacting heavily on the function of society; power cuts reduce productivity, road works cause transport delays and increased pollution from cars, and reduction in digital connectivity impacts upon all economic sectors.

Our future vision is of a society where infrastructure engineering is undertaken with zero disruption to human activity and zero environmental impact.

Robots and Autonomous systems (RAS) will play an important role in achieving this vision. Most disruption is caused by activities required to provide human operatives with safe access to infrastructure artefacts. We must dig trenches to access pipes, build gantries to access overhead cables, or close roads to protect those working on live carriageways. In contrast, RAS can operate in dangerous and challenging locations, such as inside underground pipes, or at height underneath bridges, or on live roads to perform inspection, repair, maintenance and removal tasks. This will positively disrupt the infrastructure engineering sector by improving speed, quality and timeliness of infrastructure engineering whilst reducing direct costs, economic impacts, material waste, energy usage, environmental damage, and risk to human operators.

The UK is in an excellent position to exploit these benefits. We have a dense, mature infrastructure that needs frequent interventions, and we have world-leading commercial and academic expertise in RAS. But societal and technological barriers need to be overcome to achieve the full potential of RAS in Infrastructure Engineering to be realised. This white paper highlights four key action priorities:

- Investment in interlinked basic research and technology transfer is required to pull advanced robotic technology into infrastructure engineering; only a small amount of UK government funded robotics research has been allocated to develop infrastructure robotics.

- Investment into the whole infrastructure supply chain will be needed to support uptake, training and new business models to accommodate the autonomous future.

- Industry and Universities should work together to develop test facilities where infrastructure robots can be allowed to gracefully fail, and be evaluated and improved. With a few exceptions, current test facilities are small-scale, fragmented and uncoordinated and industry will need financial and commercial incentives and protection to share, operate and manage test facilities that advance the development of robust robotic solutions for the benefit of the sector.

- Infrastructure robotics should be developed in partnership with the general public and community organisations to tackle perceived challenges around loss of jobs. Programmes should be put in place to train the next generation of "robot-savvy" infrastructure engineers, including advanced apprenticeships, degree programs and doctorial training schemes.

> Our future vision is of a society where infrastructure engineering is undertaken with zero disruption to human activity and zero environmental impact. Cities will be proactively maintained by teams of autonomous robots that will generate and process information about the health state of different assets. Infrastructure robots will draw on data from smart cities and autonomous cars using advanced communication systems and cloud technology, undertaking reasoning and schedule repairs using sophistic artificial intelligence algorithms.

CONTENTS

1. INTRODUCTION

The infrastructure sector supports the entirety of the national GDP, without which, there would be no economic activity. The UK Government has recognised this and committed to spend over £500 billion on high quality infrastructure projects by 2020-21 alone [1].

Our economic infrastructure system of systems is composed of the dense networks of energy, transport, water, waste, telecommunications and flood defences that provide the essential services on which we depend. Those networks are elderly and under heavy pressure as society demands ever-increasing levels of service from existing facilities.

Key priorities of the infrastructure engineering sector include the affordability of deploying new facilities and reducing the cost of maintaining and improving existing systems. Upgrade of infrastructure can be driven by changing patterns of demands, such as the growing and aging population or the introduction of new infrastructure technology. There is a desire to mitigate and adapt infrastructure to the effects of climate change, which includes decarbonisation of all aspects of infrastructure provisions, as well as adapting facilities to deal with the consequences of climate change, such as increased flood defences.

The ever-increasing complexity of infrastructure networks with growing interdependencies means that, while they have benefitted from the automation of manufacturing machines and components, the installation and maintenance of infrastructure assets has struggled to move beyond mechanisation to automation. Increasing demands drive a trend towards automation of all parts of infrastructure provision and operation with significant opportunity for robotic solutions.

Robots can operate across the full range of infrastructure inspection, maintenance and repair task working in the air, on the ground, in water and underground. They bring a number of distinct potential advantages over traditional human-based practices:

- Greater accuracy: Precise and repeatable operations beyond the capability of humans are achievable.
- No uncertainty of human factors: Repetitive and mundane operations can be delivered with greater repeatability.
- Faster operation: Activities can be performed in a shorter period of time.

Pre-Investigation

Inspect ground conditions & archaeology of site prior to commencement of works.

Site Surveys

Precise measurements aspects of the site; on land, in air and underground.

Monitoring

Continuous monitoring to ensure safe and successful operations, for example piling, and earth removal.

FIGURE 1.

Standard tasks undertaken as part of infrastructure engineering

- **Improved safety:** Humans do not need to undertake risky activities.
- **Improved efficiency and higher productivity:** The input energy and materials are less to create the same outcome, resulting in financial gains but also the environmental benefits of lower energy consumption and fewer wasted materials.
- **Better jobs for humans:** To free humans from the need to undertake dirty, dull and dangerous jobs.
- **Proactive action:** Robots can undertake more frequent inspections of difficult to access locations, catching defects early and preventing escalation of damage.
- **Low-cost:** The same outcome can be delivered with less cost using robots.
- **Greater insight:** Predicting and understanding "future" asset health through advanced sensing and artificial intelligence algorithms will impact on the full life cycle of infrastructure.

The convergence of RAS with the ability to embed intelligence into assets, extract intelligence from big data and the development of new manufacturing materials and processes has created a platform to overcome the complex engineering challenges associated with installing and maintaining infrastructure networks. The companies that successfully deploy and exploit RAS will be at the forefront of the fourth industrial revolution. In addition to providing an unparalleled customer experience, it is likely that these firms will unlock value chains that generate completely new economic activities.

One intriguing aspect of increased automation including robotics will be the effects on society. Infrastructure creation and operation has traditionally provided work for many of the lower skilled in society. Trends towards robotics will however demand more high-level skills from the ever-reducing numbers of people employed in the industry. A trend towards increased use of robotics will make those vital industries more attractive to the tech savvy youth of today, providing the technological stimulus to attract the next generation of engineers and new start-up companies.

Construction & Creation

Improvements in the speed, quality, and safety of infrastructure creation that recently includes advances in off-site fabrication technologies.

Maintenance

Regular repeated operations over infrastructure lifetime to ensure effective operation.

Repairs

Removal, replacement modification, and augmentation of in situ live infrastructure.

Dismantle & Dispose

Taking apart structures through unfastening or breaking and harvesting material for environmental disposals.

2. FUTURE VISION

The future vision is of a society where infrastructure engineering is undertaken with zero disruption to human activity and zero environmental impact. Cities will be proactively maintained by teams of autonomous robots that will generate and process information about the health state of different assets. There will be no separation between sensing and repair; robot teams will be capable of performing both tasks seamlessly. New infrastructure will be autonomously created by robots on-site. Infrastructure robots will draw on data from smart cities and autonomous cars using advanced communication systems and cloud technology, undertaking reasoning using sophistic artificial intelligence algorithms. This future will result in a healthier, happier, and more productive society.

The ‘Engineering and Physical Research Council (EPSRC)’ delivery plan launched in 2016 [4] targets four societal challenges:

Productive Nation: The UK production of high technology products and delivery of services is dependent on the supply of core infrastructure such as water, electricity and gas. The products created need to be transported quickly through road and rail infrastructure across the country and overseas.

Healthy Nation: Improved infrastructure can support advanced hospital services, improved roads can reduce transport delays and associated pollution and enhanced pipe maintenance can prevent pollution of water and the environment.

Resilient Nation: Better maintained infrastructure will offer greater resilience to natural or man-made changes that could be dynamic or occur over extended periods of time. Robotic systems could quickly repair and restore the operation of damaged infrastructure.

Connected Nation: Our rapid technological advancement is likely to result in new services and systems that we haven’t yet imagined requiring enhanced digital connectivity between people and organisations across the world. Robotics and Autonomous systems will have an important role to play in the rapid deployment and maintenance of these new infrastructures.

3. UK STRATEGY AND INVESTMENT IN INFRASTRUCTURE ROBOTICS

The UK research funding agency ‘Engineering and Physical Research Council (EPSRC) [2]’ supports UK fundamental research into Robotics and Autonomy with a portfolio of over 100 projects of value in excess of £100M. Approximately a quarter of research funding supports medical robotics, and another quarter supports research into fundamental autonomy challenges. Approximately 10% of robotics research funding supports infrastructure robotics with half of these projects supporting nuclear decommissioning research.

The UK research funding body ‘Innovate UK’ [3] invests at higher technology readiness levels and committed £561M towards research across all sectors in the 2016/17 financial year. Infrastructure received 27% of this funding for projects in building construction materials and energy efficiency improvements within existing buildings, mostly using conventional infrastructure engineering approaches.

To provide a context of infrastructure market value, the UK market for Offshore Wind Turbine Operation and Maintenance is valued at £2Billion by 2025 [5].

Example research projects include:

- Flexible Robotic Assembly Modules for the Built Environment (FRAMBE) [6]: This project was supported by Innovate UK and EPSRC in 2015 through ~£800K of funding to develop ‘Flying Factories’ where construction processes are undertaken in a temporary factory offsite with the aims of increasing productivity, improved quality and reduce costs. The project is led by Skanska, along with ABB Robotics, Building Research Establishment Ltd, Exelin Ltd, Tekla UK and the University of Reading.
- Project GRAID [7]: Project GRAID is funded in 2014 by £5.7M of OFGEM funds and is a collaboration between National Grid Gas, Synthotech Ltd, Premtech Ltd and Pipeline Integrity Engineers. They are developing robots to inspect high pressure gas distribution pipes with the ability to withstand 100 bars of pressure, 5 times the maximum pressure that would be normally be experienced by a submarine. The robot will have the ability to move inside live gas pipes while recording visual and wall-thickness measurements to characterise the condition of the pipes.
- Balancing the impact of City Infrastructure Engineering on Natural systems using Robots [8]: This project aims to use robots to remove disruption caused by infrastructure inspection, maintenance and repair tasks. The project is supported by £4.2M in 2016 from EPSRC as a Grand Challenge and led by the University of Leeds in collaboration with the University of Birmingham, Southampton and University College London in collaboration with a broad industrial base. In particular, the five-year project seeks to minimise the engineering required for a specific task to rebalance the energy, resource and risk undertaken in infrastructure maintenance and modernisation.
- Holistic Operation and Maintenance for Energy from Offshore Wind Farms (HOME-Offshore) [9] brings together experts from the Universities of Manchester, Warwick, Cranfield, Durham and Heriot-Watt University. The project is supported through £3M of EPSRC funds and £1M industrial contribution started in 2017. The researchers will create remote inspection and repair technologies to inspect offshore wind farms.

4. GLOBAL STRENGTHS AND TRENDS

The last 5 years have seen a major investment in robotics from governments worldwide with the EU, USA, Japan, and China investing billions of pounds into RAS research [10]. Many countries have focused on the established benefits of robotic automated manufacturing.

However, across the World, countries are beginning to recognise the value of robotic systems to create, inspect, maintain, repair and dismantle infrastructure technologies with major programmes and projects in the European Union, USA and Japan.

In Europe, significant investment has been placed into the topic of Infrastructure robotics (under the theme of 'Civil Robotics'). For example, over the period 2007-2013, the EU invested over € 135m through the EU FP7 framework in areas such as collaborative control, underwater robots, human-robot interaction, and aerial vehicles [11]. Beyond FP7, investment has continued as part of H2020. For example, the 'AEROWORKS' [12] project is an EU project funded through ~3.5M Euro through the Horizon2020 programme that aims to create autonomous aerial workers with the ability high mapping fidelity, manipulation dexterity and mission dependability. AEROWORKs is a collaboration between Lulea University of Technology (Sweden), Swiss Federal Institute of Technology (ETHZ, Switzerland), Royal Institute of Technology (Sweden), University of Twente (The Netherlands), University of Edinburgh (UK), University of Patras (Greece), two aerial robotics innovation SMEs (Ascending Technologies, Skybotix), as well as the service robotics specialists of Alstom Inspection Robotics and Skelleftea Kraft.

In Japan, it is predicted that infrastructure maintenance and repair might increase by 190 Trillion Yen (£1.3 Trillion) in the next 5 decades. The Infrastructure, Maintenance, Renovation and Management programme, commenced in 2014, aims to tackle the reliability and sustainability of civil infrastructure in Japan [13] with an annual budget of ~£20M. The overall programme is defined in 5 key stages: 1) Inspection, monitoring and diagnostics technologies 2) Structural materials, deterioration mechanisms, repairs and reinforcement technologies 3) information and communication technologies 4) Robotics technologies 5) Asset management technology.

In the United States of America, the position paper 'From Internet to Robotics' [14] defines a robot map for US Robotics. Infrastructure inspection, maintenance and repair is categorised under professional service robots to include inspection of power plants and infrastructure such as bridges, and logistics applications. This domain is expected to increase by 20% - 30% annually. The military funded 'DARPA fast lightweight autonomy program' [15] has pushed the frontiers of autonomous operation with current technology. The FAA has recently implemented new programs that allow for more flexible operation, including exemption for commercial operators and the 'Small UAS Rule' for operating aircraft under 55 lbs. These new operational rules have the potential to open up infrastructure for robotic inspection, maintenance and repair although restrictions on line of sight and daytime operation are still significant barriers to widespread uptake.

The Aerial Robotic Infrastructure Analyst (ARIA) [16] project is a collaboration between Carnegie Mellon University and Northeastern University and funded by ~$2M between 2013 and 2017 through the National Science Foundation's National Robotics Initiative. The project aims to develop new methods to rapidly model and monitor infrastructure using small, low-flying robots.

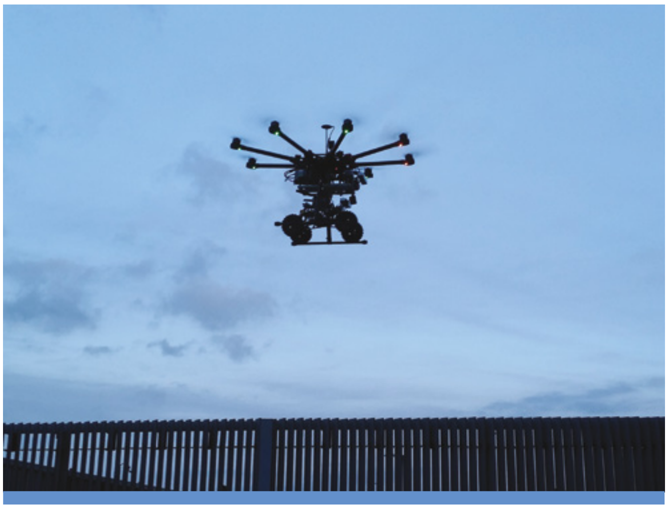

Image 1
An autonomous drone transporting ground inspection robot to a remote survey site

5. OPPORTUNITIES AND BENEFITS

The UK Government has committed to spend over £500 billion by 2020-21 on traditional infrastructure projects alone [1]. This increased investment has the aim of delivering improvements in four societal challenges. Infrastructure robots have the potential to support these societal challenges.

1. **Supporting growth and creating jobs.**
   The use of robotics in construction will have an impact on the labour market and in construction. Deloitte shows that out of 2,607,000 jobs in real estate and construction, 34% are high-risk, 15.5% medium-risk and 50.6% are low-risk [17] of being lost to automation, although the figure is 24% at high-risk according to Price Waterhouse Cooper [18]. However, research also shows that robotics creates jobs as shown by the International Federation of Robotics [19]. For example, the US automotive industry installed more than 60,000 industrial robots between 2010 and 2015 and the number of employees increased by 230,000 in the sector.
2. **Raising the productive capacity of the economy.**
   It has been shown many times that expanding productive capacity requires investment in research and innovation. Equally robotics has been identified as one of the most obvious vehicles to increase capacity.
3. **Driving efficiency.**
   Using the manufacturing industry as proxy, Boston Consulting Group [20] shows that as a result of higher robotics use, average manufacturing labour costs will be 33 percent lower in South Korea and upto 25 percent lower in China, Germany, the US, and Japan than they otherwise would have been. Similar efficiency benefits can be expected in the construction industry.
4. **Boosting international competitiveness.**
   The UK is a research power both in robotics and infrastructure subjects. Equally in the industrial sector, UK Consultancies are amongst the biggest and most successful around the World. However, UK Contractors, compared to others in Europe, are less successful in exporting. Robotics presents an opportunity to provide a competitive advantage to Contractors, whilst maintaining and enhancing the global standing of research institutions and Consultancies alike.

The construction industry has a very fragmented taxonomy that is a barrier to innovation. Most companies are very small SMEs that comprise the most significant financial share of the market, whilst only very few large companies employing more than 1,200 employees exist and have a market share lower than 20%.

Hence, to achieve the Government's intended benefits within the construction industry will require significant investment at all Technology Readiness Levels (TRLs) spanning from fundamental research to maintain the UK's strong position to commercial enterprises. This will need to include public and private sectors SMEs, large construction companies and universities.

Focus must be placed on maintaining and enhancing research in infrastructure robotics where the UK is currently World-leading, whilst developing new construction robotics technologies that will give UK Contractors a competitive advantage. Additionally, substantial funds will need to be spent on training and to make sure that the fragmented supply chain consisting of small SMEs are not left behind and can benefit from it as well. New business models will be needed to implement this future at industry level which will require either significant internal investment or, more likely, pump-priming public money to promote this change.

• Fire and Forget

Robots designed to operate indefinitely, performing inspection, repair, metering and reporting tasks (e.g. robots operating in live water mains)

• Perceive and Patch

Swarms of vehicles for autonomous inspection, diagnostics, repair and prevention of defects (e.g. potholes)

• Construct and Confirm

Coordination of robot teams to build/print, finish and certify infrastructure from CAD models using environmentally friendly building materials.

• Data and Decisions

Create, process and interpret data securely for effective, verifiable and trustworthy operation of robots interfaced through advanced communications with the smart city (e.g. robots to remotely augment building information models through the cloud).

Dismantle and Dispose •

Advanced manipulation in extreme environments to manipulate, cut, separate, and unfasten structures (e.g. nuclear de-commissioning)

Plunge and Protect •

Autonomous robots with the ability to perform underwater or underground infrastructure inspection, repair, and preventive defect maintenance.

Perch and Repair •

Remote inspection and maintenance of structures at height (e.g. bridge inspection)

6. ROBOTIC TECHNICAL CHALLENGES

Seven robotic technological barriers are identified that currently restrict the wider adoption of robotics technology for infrastructure delivery. They are termed here: Perch and Repair, Perceive and Patch, Construct and Confirm, Dismantle and Dispose, Plunge and Protect, and Fire and Forget. Application of these core robotic technologies is dependent on Data and Decisions obtained and processed locally or accessed remotely through data 'cloud' technology. These challenges will establish the technological building blocks for future infrastructure robotics. Alongside technological challenges it is also important to address the wider issues of openness and sharing; assurance and certification; security and resilience; and of public trust, understanding and skills [21].

Future exemplar 1: Long term deployment of water pipe inspection robots.

Robots will be deployed within live water systems to inspect, repair and maintain pipes from the inside without direct human control for years at a time. Advanced planning and control algorithms will manage the robot energy use in synergy with internal water flow conditions measured by the smart city. Robots will wirelessly recharge by capturing energy from flowing water and intermittently dock at wireless charging and communication points built into new advanced infrastructure. Prior to deployment, on board autonomous algorithms will be validated and verified through formal mathematical approaches, high fidelity simulations and 'real' test environments to ensure safe and effective operation. Robots will adapt autonomy in the presence of wear or damage (for example reducing speed to ensure safe operation) and the embedded systems (sensors and electronics) will align with emergent standards (such as IEEE1687) that requires an online health check capability.

Autonomous optimal planning systems will co-ordinate the actions of thousands of robots across pipe systems. Leaks within pipes will be automatically repaired by mechanical action to prepare the existing infrastructure (e.g. drilling and grinding) and then depositing advanced materials (for example new resins) that seal joints.

As well as increasing the reliability of water supply, using RAS in this manner will remove the need to dig up and disrupt roads to access water pipes, and will allow defects to be 'nipped in the bud' at the millimetre scale, before damage caused by leakage, leading to e.g. sinkholes and gross pipe fractures, can occur.

Future exemplar 2: Autonomous bridge repair

Robots will enable the rapid inspection and repair of live bridges. A database of 3D building information models (BIMs) of infrastructure (e.g. bridges, plants, buildings) will be recorded and stored remotely in the 'cloud'. UAV paths to inspect these structures can be planned in advance and adjusted locally 'on-the-fly' according to the condition of the infrastructure encountered. The UAVs will communicate using new 5G+ communication technology that will offer extremely high data rates and low latency. The ambition of 5G+ is to deliver 1000X the data rate and network capacity with 1000X lower latency. The advanced communication capability will enable UAVs to have reduced on-board processing power for decision making for improved energy efficiency and reduced cost.

UAVs will undertake sophisticated landing manoeuvres to 'perch' on structures and undertake contact measurements that may include high frequency radar signals to see through structures and dielectric measurement to determine the condition of infrastructure materials. Preventative maintenance may be undertaken directly by the UAV depositing material or undertaking small repair tasks.

More extensive repairs requiring removal or construction of infrastructure will be undertaken by larger robots. These robots may need all-terrain capability to access the site and be able to operate at height by either deploying robotic masts to reach heights or climb structures. When the work location is reached, the robot will prepare the area which may involve dismantling or cutting away damaged components. New materials will then be added through 3D printing of advanced materials or integration of new externally manufactured components.

The whole operation will take place without road closures for people or traffic or direct human control. This removes the need to close of carriageways to allow safe human access, the need to erect temporary gantries for inspection, and allows small defects to be remedied before they can escalate.

Remote Applications in Challenging Environments (RACE)
The UK Atomic Energy Authority's new centre for Remote Applications in Challenging Environments (RACE) opened in May 2016 and is based at the UKAEA's Culham Science Centre in Oxfordshire. RACE has helped UK industry to compete for and win over £150 million advanced robotics contracts, and the team has already grown by over 50 per cent. RACE develops and builds robotics and remote operations systems with a particular focus on the nuclear sector. It also collaborates with experts in space exploration, petrochemical and infrastructure to ensure that the UK maximises opportunities to transfer technology between sectors. A recognised world leader in remote inspection and maintenance in fusion reactors, RACE designed and operated the remote handling system for JET, the Joint European Torus reactor. In February 2017 RACE became a Strategic partner to the UK-RAS Network and joined a prestigious list of scientific and technology partners - including The Royal Academy of Engineering, the Institution of Engineering and Technology, the Institution of Mechanical Engineers and the Science Museum – in supporting the UK-RAS Network's mission to the advance the UK's leadership in robotics and autonomous systems.

Fawley Power Station
Fawley Power station, on the coast of the Solent, has now been decommissioned. The new owners have ambitious plans to develop an innovation hub on the site with Autonomy being an important theme. Whilst the 33 acre site is being developed the owners (http://www.fawleywaterside.co.uk/) are supportive of it usage for Robotics and Autonomy exercises and experiments by the EPSRC RAS community. The site is ideal for such exercises as most of the industrial infrastructure remains intact. The site includes a 150 metre dock area and so permits experiments with maritime (surface and underwater) robotics". However, resources will be required to manage the safety and logistics to open the site to the wider community.

7. FACILITIES FOR ROBOT DEVELOPMENT AND TRIALS

Access to real world facilities is critical to develop, test and evaluate successful robotic systems for infrastructure engineering. Realistic test scenarios will allow robots to gracefully fail enabling analysis that will accelerate the development of devices with robust operation. Technology transition from experimental research labs to 'real world' external sites should be seamlessly integrated. Current test facilities are small-scale, fragmented and uncoordinated (with a few specific exceptions, such as the Remote Applications in Challenging Environments (RACE) centre). Industry and stakeholders will need financial and commercial incentives, along with protection to share, operate and manage test facilities that advance the development of robust robotic solutions for the benefit of the sector. For example, Fawley power station offers significant potential to be used as a RAS site, but will require additional resources to be widely accessible for RAS research. Future RAS testing facilities will need to accurately represent infrastructure challenges in environments including cities, power stations, construction sites, underwater structures, offshore wind turbines, railways, roads and demolition sites. Real world facilities need to be linked to lab scale, and prototype scale facilities to ensure successful and rapid commercialisation of technologies:

- Lab scale: Specific elements of real infrastructure should be recreated in research lab environments (i.e. a pipe, a bridge bearing, wind turbine, etc.) incorporating some elements of the real operational environment, for example perturbation in temperature and wind conditions.
- Prototype scale: 1:1 large scale testing facilities in dedicated research areas that are designed to stress test prototype systems in close to operational conditions, but under tightly controlled conditions enabling specific failure modes to be investigated (for example strong winds).
- Real-world scale (Living Lab): Robots would be deployed on real assets under human accessed controlled conditions to allow their operational performance to be stressed to graceful failure.

Real environments provide a rich set of challenges that are difficult to recreate within lab conditions. Conversely, extreme operational conditions are difficult to recreate on real infrastructure. A multi-layered test environment provides a seamless transition from research lab to commercial real world deployment.

Image 2
A drone inspecting power lines

8. SOCIETAL CHALLENGES

People often feel a deep unease that the introduction of robots and automated systems into infrastructure engineering will lead to job losses and the shrinking of the workforce [22]. They imagine a tireless, unwaged army of machines replacing the workers that currently maintain our roads, railways and underground systems. These fears are fuelled by the predictions of senior figures; the Governor of the Bank of England's was reported as predicting the loss of 15 million jobs to robots [23].

The introduction of any new technology, let alone one as radical as RAS, will always change the distribution of jobs in a sector. But this need not be for the worse overall. In the infrastructure sector, many current jobs are dirty, dull and dangerous. Maintaining our buried infrastructure of pipes, cables and wires involves working in deep excavations; upgrading our electricity, communications and street lighting networks means working at heights; looking after our roads and railways can put people in the path of live traffic. All these activities put operatives and the public at risk of injury or worse. The time taken to finish many maintenance tasks is often dominated by routine preparatory or remedial work (i.e. digging holes and filling them back in) which either wastes the time of skilled workers or creates low-quality jobs that do not give workers the chance to become skilled. It is these jobs that robots should replace, freeing up our workforce to tackle the more complex, creative and challenging issues facing our ageing infrastructure. The infrastructure industry is desperately short of workers, particularly at higher skill levels. Reducing the unskilled workload will give the industry the opportunity to retrain existing workers rather than be forced to recruit from abroad.

The design, manufacture, commissioning, supervision and maintenance of infrastructure robots will create a new industry with new jobs, as will adapting the infrastructure we have now to make it easier for the robots to navigate and operate. Research should tackle social issues head-on alongside technical research in collaboration with policy makers through bodies such as Institute for Civil Engineering and the Royal Academy of Engineering.

It is important to consider environmental issues as part of the value of adopting RAS for infrastructure engineering. Pro-active maintenance has the potential to identify and repair defects quickly minimising damage, the scale of subsequent repair, and allowing infrastructure assets to be kept in service for longer. By increasing the reliability and resilience of infrastructure, it also minimises the environmental pollution caused by e.g. traffic congestion as a result of streetworks, or the displacement of animals and materials from large excavation works. Improved resilience of pipe networks will help to conserve fresh water and prevent pollution of our natural environment by fugitive sewage.

Image 3
A reconfigurable robot inspecting drains

9. RECOMMENDATIONS

This White Paper has built the case for infrastructure robotics investment, developing a world-leading UK robotics sector that can assist the Government in achieving its key strategic priorities: Supporting growth and creating jobs; Raising the productive capacity of the economy; Driving efficiency; Boosting international competitiveness.

For its realisation, three key action priorities are proposed to accelerate the uptake of robotics within infrastructure engineering:

- Investment in interlinked basic research and technology transfer is required to pull advanced robotic technology into infrastructure engineering; only a small amount of UK government funded robotics research has been allocated to develop infrastructure robotics. Investment into the whole infrastructure supply chain will be needed to support uptake, training and new business models to accommodate the autonomous future.
- Industry and Universities should work together to develop test facilities where infrastructure robots can be allowed to gracefully fail, and be evaluated and improved. Current test facilities are small-scale, fragmented and uncoordinated and industry will need financial and commercial incentives to share, operate and manage test facilities that advance the development of robust robotic solutions for the benefit of the sector.
- Infrastructure robotics should be developed in partnership with the general public and community organisations to tackle perceived challenges around loss of jobs. Programmes should be put in place to train the next generation of "robot-savvy" infrastructure engineers, including advanced apprenticeships, degree programs and doctorial training schemes.

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> Operating and maintaining our key infrastructure assets is terribly disruptive to the normal functioning of modern life. At Kier, we believe that robotic and autonomous systems have the potential to reduce, or completely eliminate the disruption caused by infrastructure failures and the activities we undertake to repair them. Developing and deploying robotic and autonomous systems requires a different engineering approach, based on cross-industry collaboration, sometimes with competitors. But the social and commercial rewards of success in this endeavour far outweigh the challenges. For us, investing in these capabilities is a no-brainer.

Paul Fletcher, MD Kier Utilities

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